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ECL 96

Development of an Undersea Power Supply at Aerojet General Corporation

In March of 1967, Mr. Carl Carney of Aerojet General's Nucleonics Division in San Ramon, California, was wrapping up plans for modifications to be included in the second prototype of Aerojet's Undersea Radioisotope Power Supply (URIPS). Mr. Carney had been working on the project since late 1965 and this prototype was scheduled to be the last design model in the URIPS series before production was started.

Prepared in the Design Division, Department of Mechanical Engineering, by William J. Clemens under the supervision of Professor Henry O. Fuchs with support from the National Science Foundation.

The URIPS (Exhibit 1) is designed to operate undersea at depths of up to 20,000 feet while generating one watt of power continuously for five years. These power units are expensive (costing about $12,000 a piece) but should provide relatively economical power where long life is necessary and access to their locations is difficult and expensive. The URIPS is primarily intended as an aid to ocean exploration and engineering operations. It is powerful enough to run : 1) acoustic transponders ("pingers") to serve as location markers for undersea test specimens and oil well heads; 2) instrumentation such as data recorders; 3) undersea survey markers to aid navigation of ships and submarines; and 4) cable "repeaters" to act as power boosters along transoceanic telephone and telegraph cables.

The primary advantage of URIPS is its relatively long operating life. Batteries have been developed that are capable of running up to two years without recharging and have a much lower initial cost than a comparable URIPS. If, however, a longer life is desired, as in most of the applications listed above, the batteries must be recovered and replaced after two years of use. Recovery of these batteries often requires the use of a ship and diver, which Mr. Carney estimated to cost about $3,000 per day from the time the ship left port to the time it returned to port. If it required more than a couple of days for a ship to recover and replace a set of batteries, it would definitely be cheaper to use a radioisotope generator.

Aerojet's Interest

Aerojet had expressed interest in developing a radioisotope thermoelectric generator (RTG) for several years. It had acquired the facilities and personnel necessary for production of an RTG during its work on other projects. The company had bid on several government contracts for development of RTG's for space applications, but had not been able to land any of them. Mr. Carney explained, "Several of the companies we bid against have had a lot of experience over the past five years ... developing radioisotope electric generators for the government. The field is very competitive and these older companies have a definite advantage because of their experience."

In 1965 the Naval Civil Engineering Laboratory at Port Hueneme, California was looking for a commercially available undersea, low power nuclear generator. It was conducting a series of long-term corrosion studies on several different materials at depths of up to 10,000 feet. The Laboratory wanted to leave corrosion samples undersea for periods extending up to five years and wanted to avoid disturbing them or the water around them until the tests were completed. A power supply was needed to run a "pinger" to facilitate the location and recovery of the samples at the end of the testing period. Storage batteries are undesirable because their two year life would necessitate replacement during the test; and this might jostle the test specimens and would add to the operational cost. For this reason, engineers at the Laboratory

concluded that the only satisfactory power supply would be an undersea nuclear generator. Since no commercial generators were yet available, they tried to get the Atomic Energy Commission to develop a suitable one. This attempt proved unsuccessful, so the Laboratory expressed its interest in purchasing a radioisotope generator to several companies, including Aerojet, hoping this would spark private development.

Encouraged by this interest and some previous customer surveys, Aerojet's Nucleonics Division in San Ramon performed a marketing analysis to see how many of these generators Aerojet could sell and what price consumers would be willing to pay for them. They then did a cost analysis based on a conceptual design provided by Mr. Carney's technical group to determine for what price the company could profitably market the generator. The results of these analyses were promising, so late in 1965, Aerojet management gave Mr. Carney's design group the "go ahead" to start work on the URIPS development.

Parametric Studies

A. Types

A radioisotope power supply converts the heat energy given off by a radioisotope fuel element into electrical energy by a variety of methods. Perhaps the most familiar is to use the heat to boil water. The steam created can then power a steam engine, which, in turn, can drive an electric generator.

A more direct method of heat energy conversion is thermionic emission. Here, an electric current is obtained by collecting the electrons emitted by a hot surface. This is the principle used to produce current in a vacuum tube by heating the cathode and attracting the emitted electrons to the anode. The use of thermionic converters is limited because they require heat sources providing fairly high temperatures (at least 2200°F) and they are hard to manufacture.

The method of generation adopted by Aerojet, however, is thermoelectric conversion. In this process, an electrical potential is developed when two dissimilar metals are joined in a closed circuit while their two junctions are kept at different temperatures, or when two ends of a doped semiconductor are kept at different temperatures. In a typical radioisotope thermoelectric generator, N- and P- type thermoelectric elements are electrically connected by conductive electrodes at each end to form thermocouple pairs and a module assembly is built up of many such pairs. One side of the module assembly is pressed against the radioisotope heat source. The other side of the module is in thermal contact with a low temperature ambient so that a temperature gradient is produced across the elements. Electricity is then tapped by means of wires from the "hot" and "cold" ends of the thermoelectric elements. An assembly of 100 bismuth telluride elements connected in series by electroplated copper electrodes, and molded into a glass filled epoxy insulating resin is shown in Exhibit 2. Two of these modules were used in the first URIPS prototype.

At the time that work was started on the URIPS program, there had been no reported development of this type of generator with the required 1 watt(e) power output. The family of developed Atomic Enery Commission power supplies ranged from 1 to 100 milliwatts, and from 5 to 500 watts. However, at this same time, Aerojet was working on an analytical evaluation of design characteristics of power supplies in the 150 to 100 milliwatt range for the Atomic Energy Commission to fill this gap. Early results of these investigations indicated that the optimum design characteristics of a generator of this size differed substantially from those employed in previous generators. Consequently, the conceptual design phase of the URIPS program included about three months of a series of detailed parametric studies. Mr. Carney explained that "these studies were necessary to give us more familiarity with the design features of the generator. We had to select those features that would give us a reliable, low cost, safe power supply that would be marketable."

The parametric studies were, as the name suggests, a series of detailed studies of the effects of design parameters of a radioisotope thermoelectric generator on cost, efficiency, size, and weight. Analyses were pefformed on the characteristics of different types of fuel, insulating materials, thermoelectric materials, and radiation shielding materials and configurations. The results from these studies provided a basis for selection of the materials and the design layout of the final URIPS.

B. Fuels

"Our marketing research indicated that if we wanted our new generator to be attractive to all potential customers, it would have to come in models with lifetimes ranging from 5 to 20 years," explained Mr. Carney. "One of our major potential customers, the telephone and telegraph companies, didn't think it would be justifiable for them to use our generators for their cable 'repeaters' unless the operating life was that long." Because of the restriction placed on the design by the generator life, only those fuels were studied which had half-lives of at least five years. Among the radioisotopes considered were Co^{60}, Sr^{90}, Cs^{137}, Pu^{238}, and Cm^{244}. Consideration of fuel cost and availability narrowed the field of candidate radioisotopes down to Sr^{90} and Co^{60}. Which of these two would be chosen depended on the one that would result in the smallest, lightest, and least expensive generator. Mr. Carney's group found that to keep the radiation at the surface of the generator down within legal limits Sr^{90} required only about half the biological shielding as Co^{60}. However, the primary advantage Sr^{90} enjoyed over Co^{60} was that it did not dissipate as much energy outside the fuel capsule as Co^{60}. A large share of Co^{60} decay energy was found to be released as penetrating gamma photons, most of the energy of which is deposited outside the fuel capsule in surrounding material. If Co^{60} were used, an inert uranium or tungsten shield would have to be placed around the fuel to trap the photon energy. Since heat

energy is generated by radiation being absorbed by the fuel capsule itself or the material surrounding it, this need for an integral shield reduces the effective "power density" of the fuel capsule, that is, the amount of heat energy generated per unit volume of heat emitting material (in this case, both the fuel source and its shield). This results in increased fuel cost due to the lower thermal efficiency resulting from larger parasitic heat lost through the insulation surrounding the heat source. Based on these results, Mr. Carney and his team chose Sr^{90} as their radioisotope fuel. Strontium titanate ($SrTiO_3$) was the most readily available form of strontium and was ideal for this application because of its low solubility in water, and established compatibility with suitable encapsulating materials.

C. Finding a Thermoelectric Material

A large number of thermoelectric materials were also investigated as part of these parametric studies. They were evaluated for what Mr. Carney described as their URIPS system electrical efficiency, η_E. This efficiency covers the thermoelectric "module" (which is the unit holding the thermoelectric elements) and the power conditioning unit needed to regulate the electrical output of the generator. The system electrical efficiency is related to the individual thermoelectric module efficiency, $\eta_{T/E}$, and the power conditioning efficiency, $\eta_{P/C}$, by

$$\eta_E = (\eta_{P/C})\ (\eta_{T/E})$$

The electrical efficiency was calculated for a number of thermoelectric materials through the use of an Aerojet computer program developed under a previous Atomic Energy Commission contract. Among the variables taken into account were operating temperatures, power output, thermoelectric material properties (electrical resistivity, thermal conductivity, and Seebeck coefficient), contact loss at the thermoelement electrodes, time dependent degradation in performance, and geometrical characteristics (thermoelement size, number, and configuration). Using the basic thermoelectric efficiency equation for matched load conditions,

$$\eta_E = \frac{T_h - T_c}{2T_h + \frac{4}{Z_E} - \frac{T_h - T_c}{2}}$$

where

T_h = hot junction temperature (°K)

T_c = cold junction temperature (°K)

Z_E = effective figure of merit (°C^{-1})

Mr. Carney's group determined an effective figure of merit for each thermoelectric material which gave a simple description of the relationship of system electrical efficiency to operation temperature. A list of some of these figures of merit is given in Table I. This figure was then used in an overall system analysis computer program which calculated the overall system efficiency (including parasitic heat losses in the insulation and fuel capsule support structure), size, weight and cost as a function of operating temperature, fuel shielding, and insulation material.

Bismuth telluride was finally chosen for use in the first URIPS because: 1) it gave the highest system overall efficiency; 2) it was economically superior to the other thermoelectric materials for power generation up to 2 watts and competitive to 5 watts; 3) the low operating temperature range needed for it makes it far easier to fabricate the generator; and 4) it had been used before successfully in radioisotope thermoelectric generators with similar electrical requirements.

D. Shielding

The ultimate size and weight of the URIPS would be determined primarily by the amount of shielding required around the fuel capsule. Local, state, and federal laws require that the maximum dose rate at the surface of the generator not exceed 200 mr* per hour. In addition, thermal insulation would have to be placed around the fuel capsule to prevent unwanted energy losses from the 46 watt heat source. (7200 curies of $SrTiO_3$).

Only two radiation shielding materials were extensively considered for the URIPS; uranium and lead. They were the only materials investigated because of their proven performance and availability. Preliminary analyses showed tungsten to be more expensive than uranium, and while iron would cost about the same as lead, it results in a significantly larger and heavier generator. Therefore, uranium was taken as being representative of the most compact system, and lead as the least expensive.

TABLE I

Thermoelectric Material	$Z_E \times 10^2$ °C^{-1}
Cupron/Tophel Special	0.10
MCC - 40	0.25
SiGe Alloy	0.30
PbTe (3N/3P)	0.40
SiGe - PbTe (2N/2P) Cascaded	0.40
PbTe (2N/2P)	0.55
PbTe (2N/2P) - Bi_2Te_3 Cascaded	0.60
Bi_2Te_3	0.90

* mr = milliroentgens

Wes Tamai and Hal Whitum, the heat transfer and radiation specialists of the team, modeled three possible configurations of shielding materials for the URIPS. "We wanted an idea of which of these configurations would give us the smallest, lightest generator," explained Mr. Tamai, "so we contrived a simplified model of the generator and calculated its size for different shielding arrangements." There were five possible configurations to test (see Exhibit 3): 1) internal uranium shield; 2) external lead shield; 3) external uranium shield; 4) partial internal uranium shield--partial external uranium shield; and 5) partial internal uranium shield--partial external lead shield. An internal lead shield couldn't be used because lead melts at typical R/I temperatures. After making a numerical-mathematical model for each of the configurations, Mr. Tamai and Mr. Whitum used a computer program to determine the size and weight of each configuration that would meet the radiation and thermal requirements.

The results of the study showed that an external uranium shield would result in the smallest URIPS diameter. However, the study also found that weights of external and internal shield configurations were about the same but a uranium split shield results in a net weight increase. Finally, a partial external lead shield increases the system weight significantly. In the limiting case, a full external lead shield system was found to weigh about twice as much as a full external uranium shield system. The full external shield configuration was selected because it provides the lowest system cost and size, and is not significantly heavier than the internal shield for this low power output.

E. Insulation

The choice of an insulating material for the URIPS depended primarily on its thermal conductivity. The lower this conductivity, the lower the heat losses and thickness of insulation required. A secondary consideration would be the physical form the insulation came in, i.e., solid, granular, liquid, or powder. If the insulation came in a solid form capable of supporting the fuel capsule, then additional energy losses caused by heat dissipation through a support would be eliminated. Also, insulation materials requiring encasement in a vacuum could not be considered because of their doubtful reliability when left unattended for long periods of time, due to outgassing and loss of effectiveness. Several insulations were examined during these parametric studies, but the most satisfactory proved to be Min-K 1301 backfilled with xenon gas. There are other insulations with lower conductivities, but they all require vacuum. It was coincidental, but Min-K 1301 was found to be able to support pressures of 100 psi (gauge) which meant that it could support the fuel without the help of independent mounts, providing allowance is made in the design for a small amount of creep.

Making the Generator a Reality

"Our parametric studies told us approximately what the URIPS was going to be like," explained Mr. Carney. "From these studies we knew the types of shielding to use and how much we needed, the type of fuel we were going to use, what type of thermoelectric material to use, and even what type of insulation would be best." The main problems now were primarily mechanical, i.e., arranging these components into a workable design. The design criteria specified that the generator be able to withstand pressures of 20,000 feet of water as well as the corrosive salt water environment for extremely long periods of time.

Following the parametric studies, which lasted about three months, Mr. Carney's group began their preliminary design period during which they made layouts of variations on their basic generator design and made decisions on how the generator was to be put together. The preliminary design, shown in Exhibit 4, is the product of this development phase.

During this period Aerojet also decided to market two models of the URIPS; a lead shielded version and a uranium shielded model. Parametric studies showed that uranium was the most efficient shielding material, resulting in the lightest, most compact generator. However, uranium is very expensive and some preliminary estimates showed that use of lead in the URIPS would result in a generator that was $3,000 cheaper than the uranium shielded model.

Shortly after the preliminary design was completed, a shielding experiment was performed to make a more accurate determination of "scattering" contributions to the surface radiation dose rate. An excessive amount of radiation scattering was found to be coming out of the flange. Ron Soulis, the URIPS mechanical design engineer, revised the initial design concept to correct this deficiency and included an integral housing for the power conditioner. The final design for the first URIPS production model is shown in Exhibit 5.

The strontium fuel is encapsulated in a Hastelloy-C capsule that is designed to withstand a pressure differential of 15,000 psi after exposure to the salt water environment for 300 years. The main reason that Hastelloy-C was chosen was its high strength (120,000 psi ultimate), and its excellent corrosion resistance. Titanium was also a strong candidate for the job, but Hastelloy is much easier to work with and it has demonstrated good chemical compatability with the fuel being used. A photo of the capsule is shown in Exhibit 6.

The thermal insulation is used to support the capsule in the generator housing. There is no pressure vessel around the insulation in the uranium model because uranium is strong enough to withstand the pressures at the design depths with no assistance. However, the lead shielded model has a medium alloy steel pressure vessel surrounding it to prevent damage to the generator and insulation. The outer shell on each of the two models is 70/30 copper-nickel alloy which was chosen for its good corrosion resistance and good workability.

The hermetically-sealed thermoelectric converter (Exhibit 7) is immediately on top of and pressed against the fuel capsule. A stainless steel bellows encloses the thermoelectric module in an inert gas (argon) atmosphere to protect it from long term contamination caused by gases evolved from the thermal insulation. The bellows also provides flexibility in the converter package to compensate for manufacturing tolerances and insulation creep. Copper "shoes" welded to each end of the bellows provide thermal contact with the lead shielding plug on one end and with the fuel capsule on the other end. Springs inside the converter keep the shoes in positive contact with the plug and the capsule at all times. These springs also force the thermoelectric modules against the split pressure plate under which is a silver wool pad to compensate for thickness variation in two modules. Heat is transmitted from the module to the "cold" shoe through a set of small copper spheres of assorted sizes which fill the cavity between the module and the shoe. The copper spheres allow expansion and contraction of the thermoelectric converter while making good thermal contact between the module and the cold shoe so that the converter can be seated properly in the generator.

The power conditioning unit is located in a removable "cap" on top of the generator and is separated from the thermoelectric converter by the shielding plug. The power conditioner transforms the low voltage (1.6 volts) d.c. power from the thermoelectric modules to the required output voltage (usually 24 volts) and regulates the output voltage to compensate for changes that occur as the radioisotope decays.

A test program was conducted to accurately determine the overall system efficiency and to determine the actual amount of fuel required for a production model URIPS. A full scale mockup of the pressure vessel, insulation, and heat source was fabricated, using an electrical heater mounted inside a copper block to simulate the radioisotope heat source. Results of initial tests on the prototype thermoelectric converter showed that the heat was not as efficiently conducted through the copper spheres as design analyses had predicted. This resulted in a larger temperature drop across the spheres which significantly reduced the system efficiency. Mr. Carney's group resolved this problem by increasing the thermal contact surface area in contact with the copper spheres by a factor of five. Additional testing was required to 'prove' the design and to establish manufacturing and processing methods.

The first URIPS production model was assembled in February of 1967 and has been used in exhibits at several technical conferences. The second production model was sold and delivered to the Naval Civil Engineering Laboratory at Port Hueneme, California, in September 1967. This later model, shown in Exhibit 8, differs from the first in that an improved thermoelectric converter was installed. This converter is now a rigid assembly with the copper balls replaced by a solid copper conductor. A support bellows placed under the fuel capsule now maintains a positive pressure between the capsule and the converter -- a job performed before by the flexible thermoelectric converter. Mr. Carney reported that his

group found out that the reduced temperature drop in the heat conducting system of the converter provides a significant performance improvement over the other converter and more than compensates for the small amount of heat (less than 1 watt) that leaks out through the support bellows. "Our initial objective of improving the efficiency and reducing the fuel cost of the URIPS by employing a flexible converter to eliminate the need for a support turned out to be untenable," explained Mr. Carney. "The fabricational complexity, which added to the system cost, and the inferior heat transfer we were getting through the copper spheres proved to be the deciding factors in changing our initial design."

Mr. Carney reports that future engineering improvements will be directed at improving the reliability of the thermoelectric module. As insurance against failure of the whole system, the thermoelectric converter in the first two models had two thermoelectric modules connected in parallel so that if one of the elements in one of them failed, one module would still be working. The main problem was that this failure would reduce the power output by one-half. To eliminate this trouble spot, his design group came up with the idea to manufacture the modules used in future production models with all the elements connected together in a ladder network as shown in Figure 1. In this case, if one out of the 100 elements gives out, the power of the unit is reduced by only 1% instead of 50% as before.

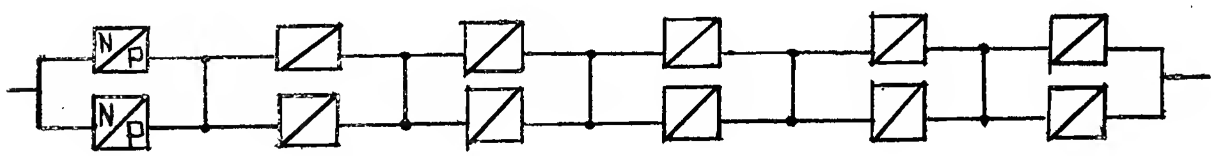

Figure 1 - Series-Parallel Redundant Network

With this electrical network, twice as many thermoelements are required to obtain the same output voltage as a simple series connected module, and they must have a correspondingly smaller cross section**. As a consequence of the requirement for extremely small semiconductor elements for the low URIPS power output, initial attempts to fabricate series-parallel modules were unsuccessful, and an alternate means of improving reliability has been substituted for the present. The total number of series-connected couples has been reduced from 100 to 36, and the electrodes are plasma sprayed onto the bismuth telluride thermoelements instead of electroplated to provide a more durable bond and higher operating temperature capability. A second URIPS employing this improved thermoelectric module was delivered to the Naval Civil Engineering Laboratory in November 1967.

** The dimensions of the previously used elements are 0.060" square by 0.200" long.

UNDERSEA RADIOISOTOPE POWER SUPPLY

**ONE WATT UNDERSEA POWER SUPPLY
CAPABLE OF 5 YEAR UNATTENDED OPERATION**

DESCRIPTION

URIPS is a radioisotope powered electrical generator designed for long duration underseas power applications. An encapsulated radioactive strontium titanate heat source coupled with a thermoelectric conversion module produces DC electric power. The fuel capsule is insulated to restrict parasitic thermal losses, encased to withstand hydrostatic pressure, and shielded to provide biological protection. A power conditioner containing a static DC to DC converter and voltage regulator is provided to satisfy a range of specific power requirements. Advantages accruing from bismuth telluride thermoelectrics include highest conversion efficiency at low operating temperature (450°F) which enables reduction of size and shielded weight and contributes to overall system reliability.

APPLICATIONS

Navigational Aids/Markers

- acoustic/visual beacons – site markers

Scientific Equipment

- data recording/transmission – oceanographic and meteorological
- timers, release mechanisms, actuators

Fixed Underwater Networks

- acoustic surveillance, cable repeaters
- detection system – acoustic splash and seismic shock

Battery Trickler

- for special duty cycles and high peak power

SPECIFICATIONS

DESIGN LIFE – 5 years for 0.98 reliability
10 years for 0.95 reliability

FUEL – Strontium Titanate in Hastelloy C capsule
Half-Life 28.8 years

VOLTAGE – 3 to 28 volts regulated DC or AC

POWER – 1 watt continuous for 5 years

OPERATIONAL ENVIRONMENT – Sea or fresh water to 20,000 ft

STORAGE AND SHIPPING ENVIRONMENT – Conforms to MIL STD 810A

THERMOELECTRICS – Bismuth telluride, static conversion, no moving parts

SHIELDING – Lead, meets AEC and ICC specs.

ENCASEMENT – 70-30 Cu-Ni Alloy

SIZE – 14 in. dia x 20 in. long

WEIGHT – 800 lb or 400 lb
(Smaller unit available at additional cost)

COST – $12,000 including license

AEROJET GENERAL TIRE GENERAL
AEROJET-GENERAL CORPORATION
NUCLEAR PRODUCTS AND SERVICES GROUP
BOX 77, SAN RAMON, CALIFORNIA, 94583 • AREA CODE

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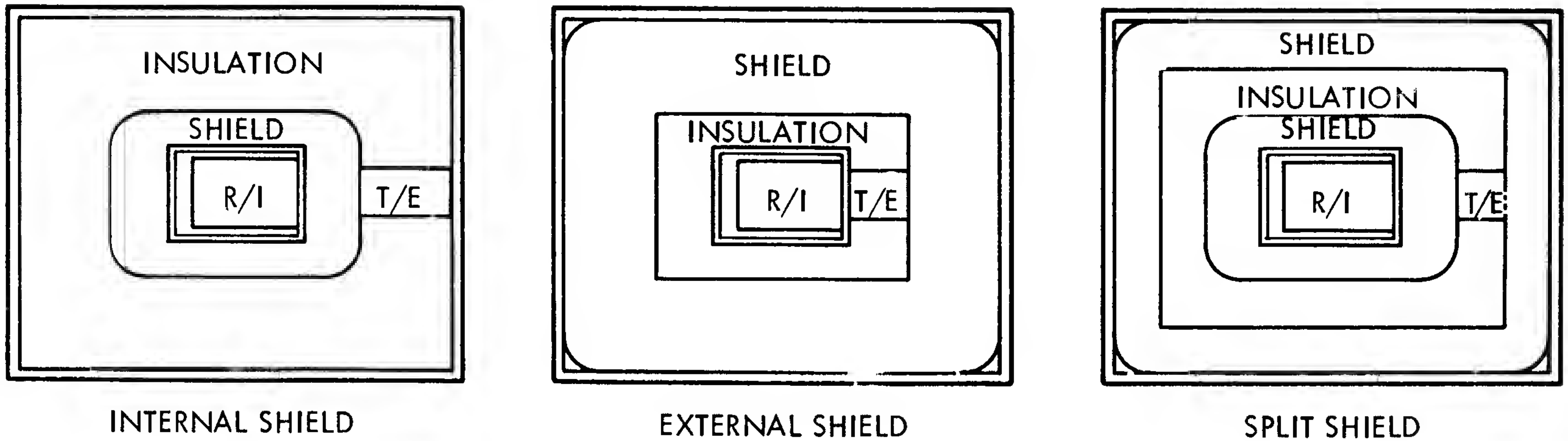
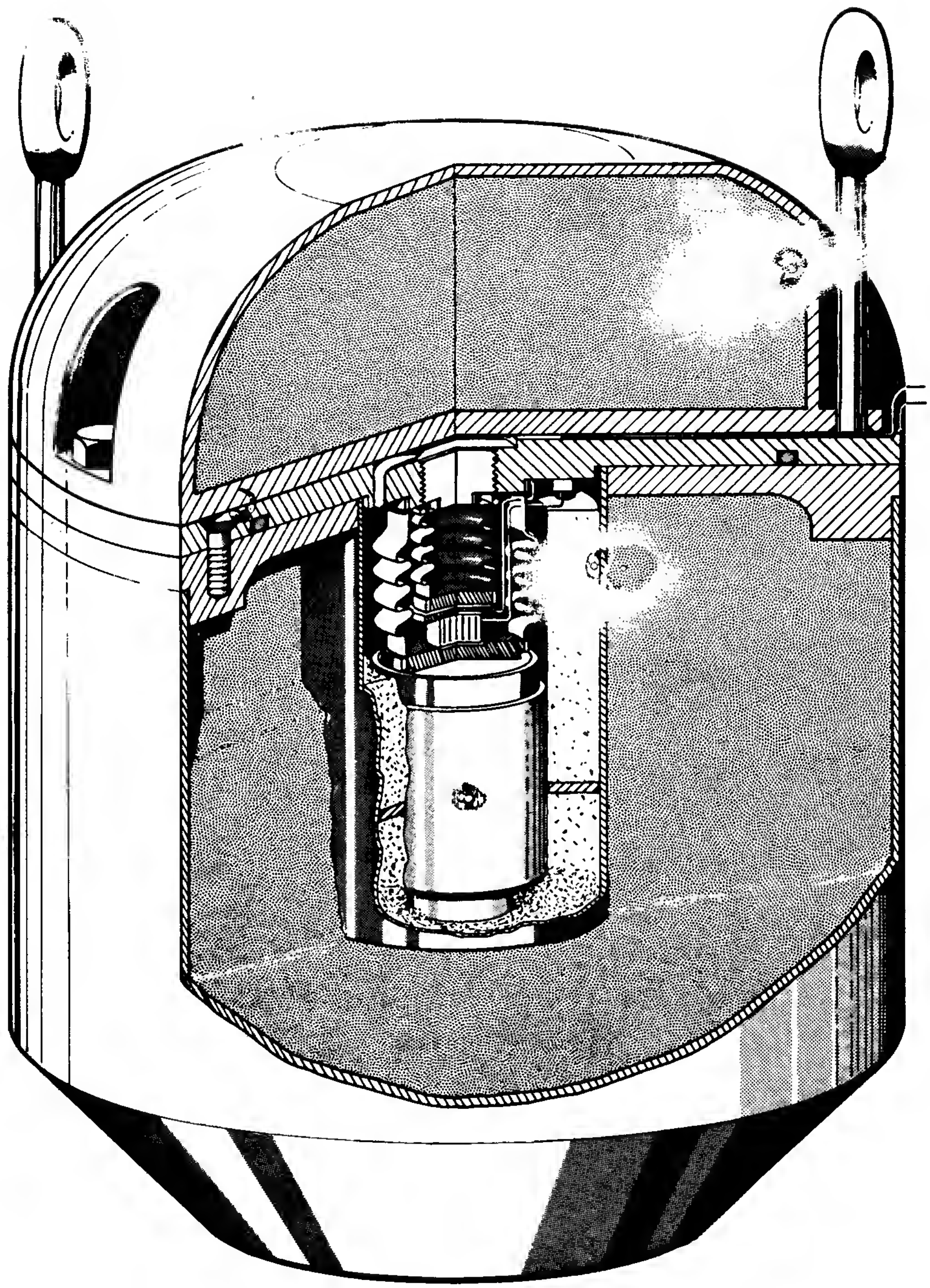
Exhibit 2

Thermoelectric Power Module Used in First URIPS Prototype

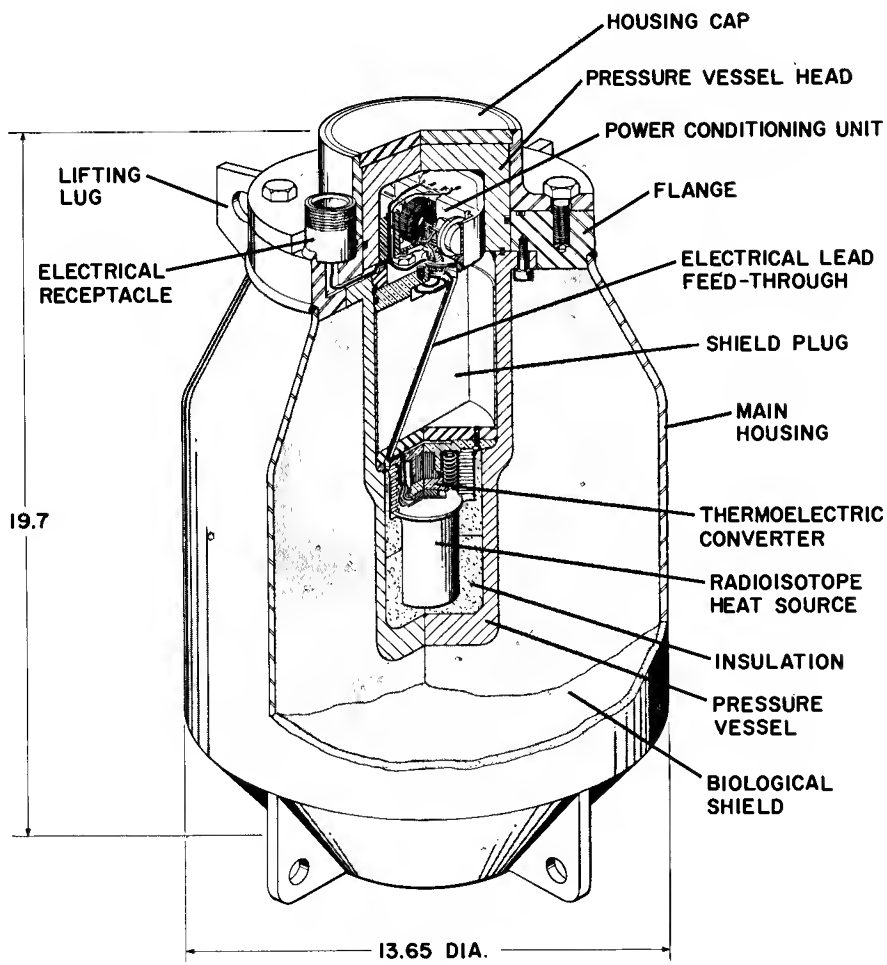


Shielding Configurations

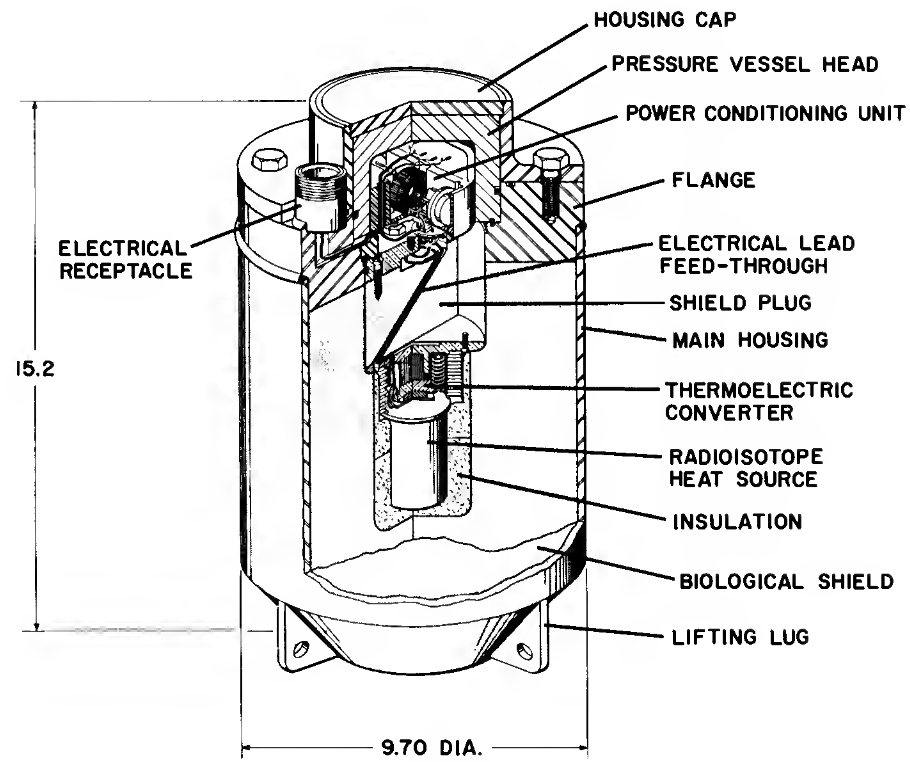


Preliminary URIPS Design (Uranium Shield)

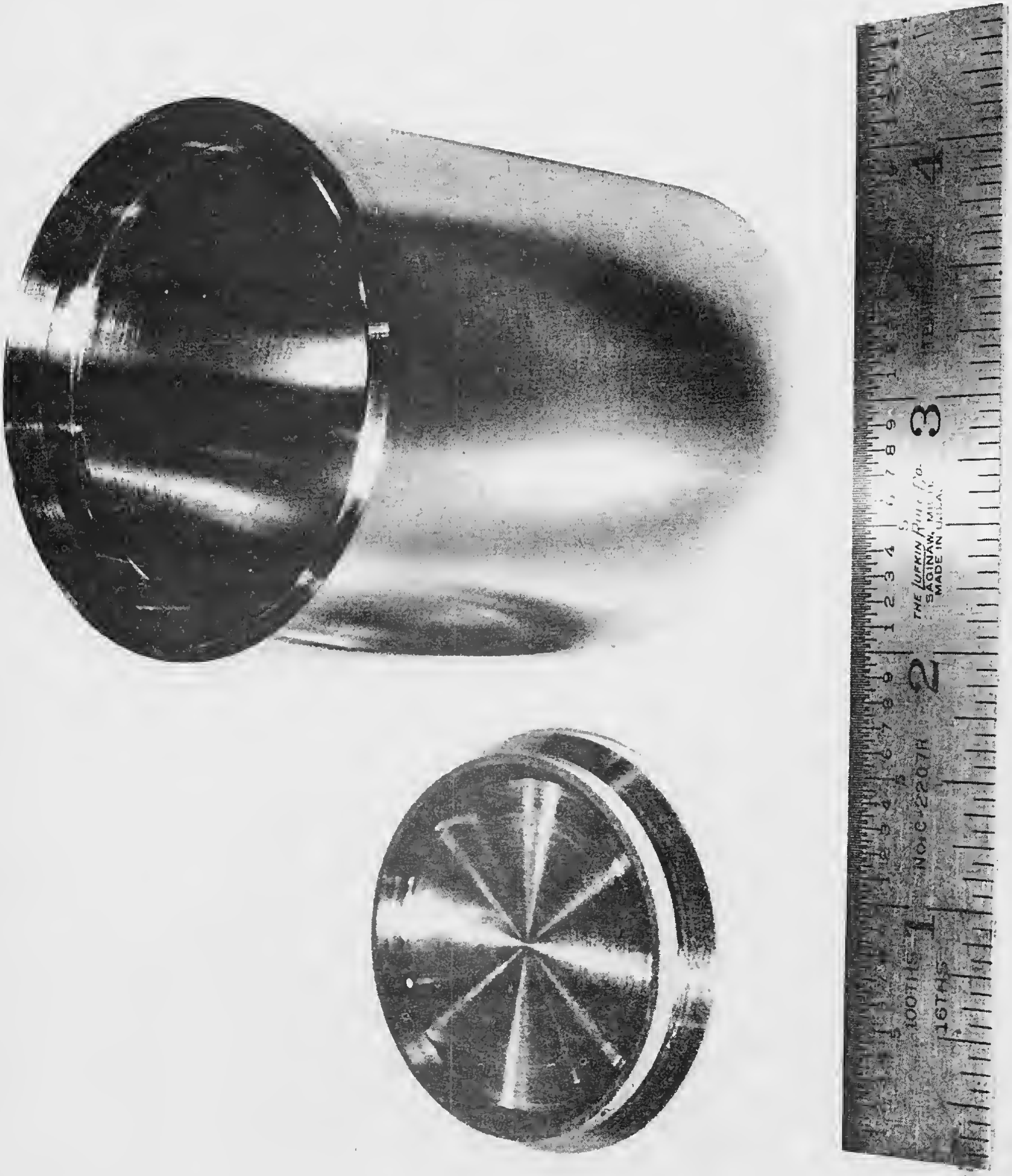
1 WATT(e) URIPS-P1, LEAD SHIELD



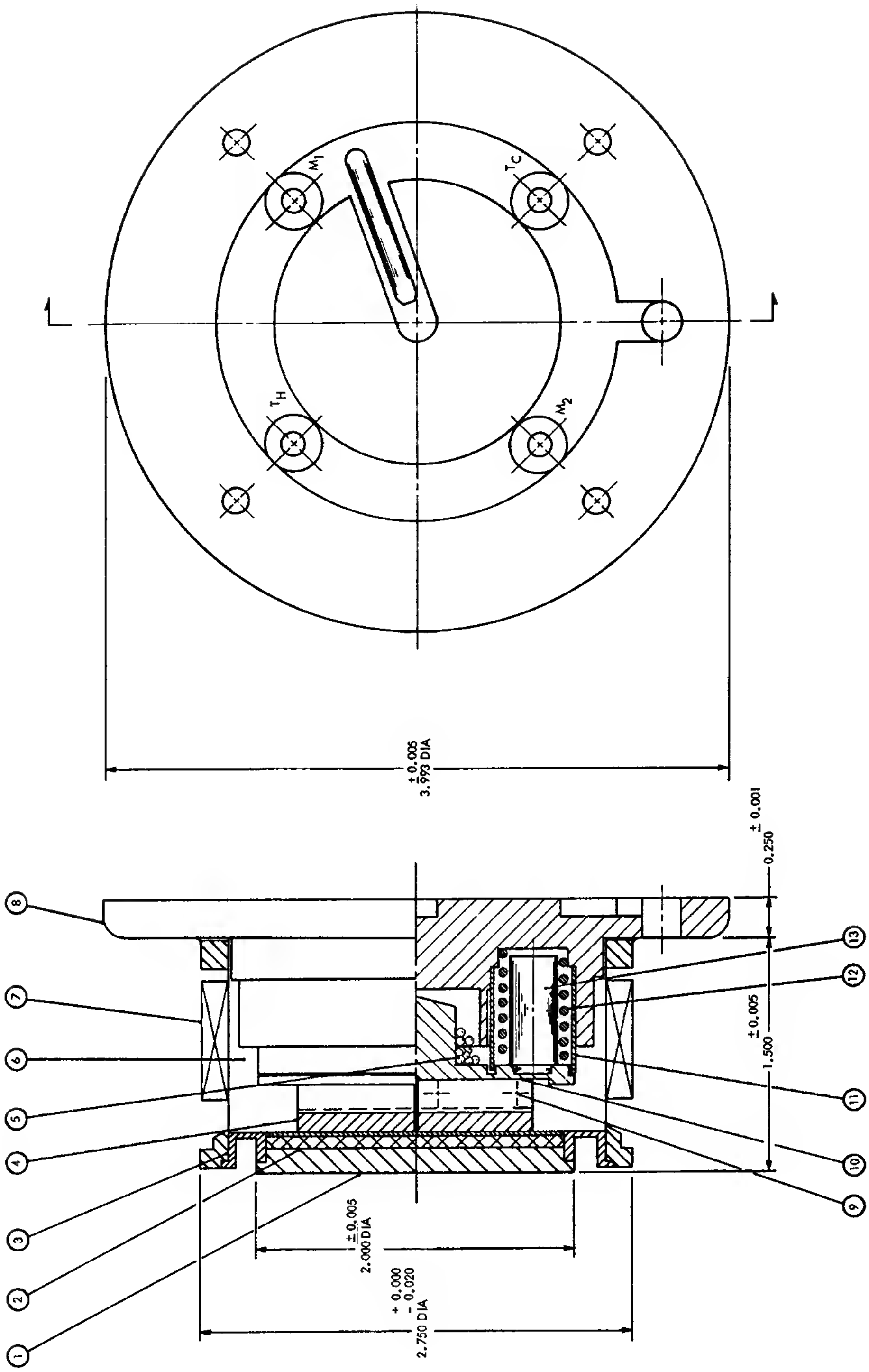
1 WATT(e) URIPS-U1, DEPLETED URANIUM SHIELD



Final Design for the First Production Model URIPS



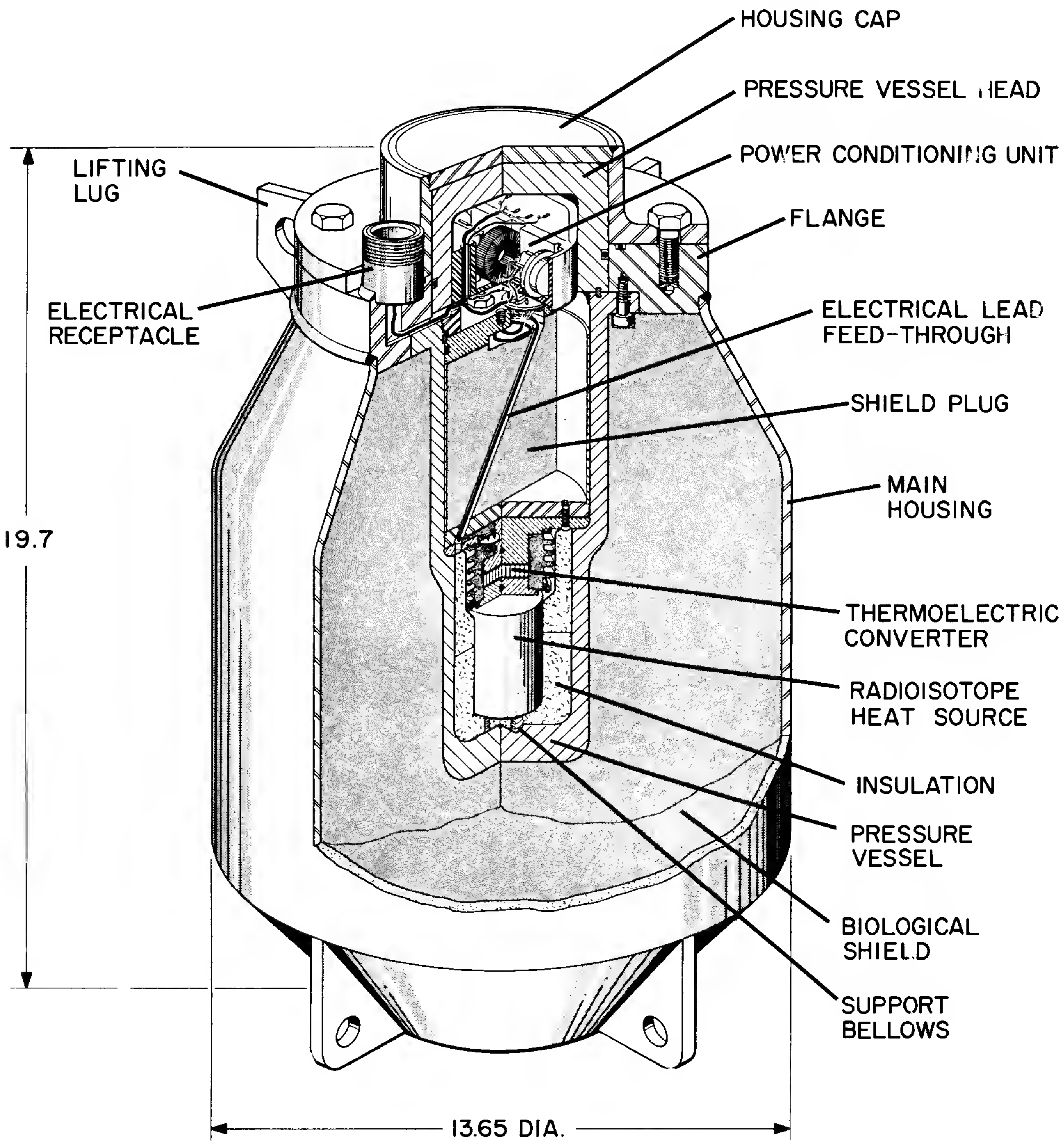
Hastelloy C Fuel Capsule



Thermoelectric Converter Used in the First Production Model URIPS

1. Copper Hot Shoe
2. Silver Wool Flexible Pad
3. Stainless Steel 304 Weld Ring
4. Copper Pressure Plates (2 each)
5. Copper Spheres
6. Fibrous Thermal Insulation (Microquartz)
7. Stainless Steel 304 Bellows Assembly
8. Copper Flange
9. Asarco Bi_2Te_3 Thermoelectric Module, Type TH1010 (2 each)
10. Copper Cold Shoe
11. Spring Guard (Copper)
12. Phosphor-Bronze Coil Springs (3 each)
13. Spring Guide (Brass)

1 WATT(e) URIPS-P1, LEAD SHIELD



Current Production Model URIPS